

M87: A MISALIGNED BL LAC?

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ABSTRACT

The nuclear region of M87 was observed with the Faint Object Spectrograph (FOS) on the *Hubble Space Telescope* (*HST*) at 6 epochs, spanning 18 months, after the *HST* image quality was improved with the deployment of the corrective optics (COSTAR) in December 1993. From the FOS target acquisition data, we have established that the flux from the optical nucleus of M87 varies by a factor ~ 2 on time scales of ~ 2.5 months and by as much as 25% over 3 weeks, and remains unchanged ($\lesssim 2.5\%$) on time scales of ~ 1 day. The changes occur in an unresolved central region $\lesssim 5$ pc in diameter, with the physical size of the emitting region limited by the observed time scales to a few hundred gravitational radii. The featureless continuum spectrum becomes bluer as it brightens while emission lines remain unchanged. This variability combined with the observations of the continuum spectral shape, strong relativistic boosting and the detection of significant superluminal motions in the jet, strongly suggest that M87 belongs to the class of BL Lac objects but is viewed at an angle too large to reveal the classical BL Lac properties.

Subject headings: galaxies: individual (M87) — galaxies: active — galaxies: nuclei — BL Lacertae objects: general

1. INTRODUCTION

Variability is a fundamental property of Active Galactic Nuclei (AGN). In fact, it was the rapid changes of the observed optical continuum flux of quasars that led early researchers to the conclusion

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that vast luminosities must be generated in a very small volume, suggesting that accretion onto a massive black hole is the source of the energy generation (Salpeter 1964, Zeldovich & Novikov 1964).

It is now understood that in the BL Lac objects rapid variability is the result of strong relativistic boosting in a jet oriented close to the line of sight to the observer (for a review see Urry & Padovani 1995 and references therein). The connection between BL Lacs and the Fanaroff-Riley class I (FR I) radio sources is now firmly established (Padovani 1992). The flux in the extended radio structure of BL Lacs lies in the same range as observed for the FR I sources.

Apart from the variability, the fundamental properties of BL Lacs are: (1) bright featureless continuum of synchrotron origin which peaks typically at IR wavelengths for the radio-selected objects (the low energy BL Lacs, or LBL) and in the UV/X-ray region for the X-ray selected ones (high energy BL Lacs, HBL – see Urry & Padovani 1995 and references therein for a description of the LBL/HBL dichotomy); (2) superluminal motions in the jets observed at radio frequencies (Vermeulen & Cohen 1994; Gabuzda et al. 1994); (3) BL Lacs are found exclusively in elliptical galaxy hosts. Because FR I radio galaxies often exhibit with LINER-like nuclear spectra (e.g., Baum, Zirbel & O’Dea 1995), and BL Lacs are thought to be drawn from the same population as FR I (see Urry & Padovani 1995), it is then likely that some BL Lacs would also display LINER type activity if the beamed continuum radiation did not overwhelm the emission lines.

The galaxy M87 (NGC 4486) shares many of these properties. Although M87 is 0.3 mag fainter than NGC 4472 (M49), it is the dominant galaxy in the largest optical component of Virgo, Cloud A (Binggeli et al. 1987), and is at the center of the corresponding extended hard X-ray component that accounts for $\sim 70\%$ of Virgo’s X-ray Luminosity (Bohringer et al. 1994). M87 is presently the best example of a small disk of ionized gas ($r \sim 100$ pc; Ford et al. 1994) fueling a massive black hole $M_{\text{BH}} \sim 2 - 3 \times 10^9 M_{\odot}$ (Harms et al. 1994, Ford et al. 1996; Macchetto et al. 1997). The gaseous disk has a classical LINER emission line spectrum, and its properties in the UV establish it as a shock heated accretion disk (Dopita et al. 1997). The “engine” in the center produces the best known example of an extragalactic optical synchrotron jet oriented at about $\sim 30 - 35^{\circ}$ to our line of sight (e.g., Biretta 1994; Bicknell & Begelman 1996). In the X-rays significant variability has recently been reported by Harris, Biretta & Junor (1997). The broad-band spectrum of the nuclear source from the radio to the X-rays is similar to that of the individual knots in the jet. The radio-to-optical index, $\alpha_{\text{ro}} = 0.81$, the optical-to-X-ray index, $\alpha_{\text{ox}} = 1.12$, and the optical-UV spectral index is 1.46 (Biretta, Stern, & Harris 1991; Boksenberg et al. 1992), making it qualitatively similar to optically selected blazars such as 3C 345 (Kollgaard 1994; Maraschi et al. 1986; Bregman et al. 1986). In fact, these values of α_{ro} and α_{ox} place M87 at the edge of the region of the $\alpha_{\text{ro}} - \alpha_{\text{ox}}$ plane populated by radio-selected BL Lacs and radio quasars (Padovani & Giommi 1995). The jet displays powerful relativistic boosting, strong internal shocks, and significant superluminal motions (Biretta, Zhou & Owen 1995). In addition this jet is powering complex radio lobes with luminosity and morphology typical of FR I sources.

The proximity of M87, combined with independent measurements of the central black hole mass and jet orientation, make it a primary target for studying some of the fundamental properties of active galactic nuclei.

In this paper we present analysis of the FOS target acquisition (TA) data for several observations of M87’s central region. The data reveal significant variations of the nonstellar nuclear source flux in the optical wavelength region. Throughout the paper we assume a distance to M87 of 15 Mpc (Jacoby, Ciardullo & Ford 1990) which simplifies comparisons with results of the latest measurements of the central black hole mass (Harms et al. 1994; Ford et al. 1996; Macchetto et al. 1997), the energetics of the LINER disk (Dopita et al. 1997), and the X-ray variability (Harris, Biretta & Junor 1997).

2. OBSERVATIONS

As part of several GTO and GO programs, the nuclear region of M87 was observed with the FOS on *HST* at 6 epochs over 18 months, following the introduction of COSTAR in December 1993. The spectra obtained at each epoch were preceded by a careful target acquisition consisting of a binary search (BS) followed by one or more pickup rasters, all using the FOS red channel in camera mode. The photocathode of the FOS red detector is sensitive to wavelengths in the 1600 – 8000 Å region, with peak quantum efficiency of $\sim 25\%$ between 2000 – 4000 Å. The binary search data comprise a series of one-dimensional images obtained by electronically stepping the target field in the $3''.7$ square aperture across the $1''.29$ tall linear diode array. For the pickup sequences, the $0''.26$ diameter circular aperture was stepped in a raster pattern over the target field utilizing small angle maneuvers of the telescope. The two types of target acquisition data yield corroborating evidence for strong nuclear intensity variations.

Fig. 1 shows the BS images of the centered nucleus at four of the epochs (the other two are not shown for clarity). Note that the underlying galactic component remains constant to within the measurement errors, while the nuclear source varies in intensity. The width of the nuclear profile remains constant at about 0.9 diode widths, which is characteristic of an unresolved point source. The insert in Fig. 1 shows the shape of the radial profile of the M87 nucleus inferred from one of the pickup series. Overplotted is a scaled profile of a star, again illustrating that the nucleus of M87 is unresolved by the *HST*. The characteristic size of the *HST* PSF at the FOS after the introduction of COSTAR is ~ 60 mas FWHM (Hartig, Crocker & Ford 1994). At a distance to M87 of 15 Mpc, the upper limit on the size of the region producing the variability is $\lesssim 5$ pc in diameter.

At each epoch we computed the nuclear source count rate when the aperture was best centered on the nucleus. For the BS data we integrated the flux above the background galactic contribution, which was approximated by a constant and left free in the fitting. The integration was restricted to a $1''.01$ region centered on the peak (see Fig. 1), which effectively represents the flux of the nucleus measured in a $1''.01 \times 1''.29$ aperture. For the pickup series we used the count rate observed at the

best centered position. The contribution from the host galaxy in the $0''.26$ circular aperture used in the pickup series was estimated to be less than a few % and was neglected. Both measurements are illustrated in Fig. 2 as a function of time, with estimates of the error and the level of the galactic component. The flux ratio between the $0''.26$ and $1''.01 \times 1''.29$ apertures is close to what is expected for the relative transmission of a point source (Keyes et al. 1995), and remains constant for all measurements. Fig. 2 shows that the nuclear flux changes by a factor of 2 over approximately 2.5 months (78 days) and by as much as 25% in 3 weeks. The flux of the nucleus did not change to well within the 1σ error bars (2.5%) for the two measurements obtained only 23 hours apart on 24 and 25 May 1995.

For two of the observational epochs a nuclear spectrum was obtained through the $0''.26$ circular aperture (Fig. 3). In both cases the spectrum is dominated by bright broad emission lines and a strong non-thermal blue continuum, similar to other types of AGN such as quasars. The continuum is well described by a power law with spectral index $\alpha = 1.4$ ($F(\nu) \sim \nu^{-\alpha}$), in agreement with that of the unresolved nuclear source determined from *HST* imaging (Boksenberg et al. 1992). The Na I line seen in absorption has the same redshift as M87 and is a neutral component of M87’s extended ISM. No other absorption features are seen, indicating that any contributions due to stellar light is small. The ratio of the two spectra plotted in the lower panel of Fig. 3 shows two important characteristics. First, the spectrum becomes bluer as it brightens. This is in good agreement with properties of the radio-selected BL Lacs which seem to display the same behavior in the IR/optical/UV band (see Ulrich, Maraschi & Urry 1997). The fractional change at $\lambda 4600$ Å is approximately 50% versus only 35% at $\lambda 6800$ Å. Second, the ratio at the emission line positions is significantly lower, indicating that the observed changes are due to a rise in the continuum level. This is best seen at the position of the bright H α + [N II] complex which is less subject to a continuum dilution. The ratio in that wavelength region drops to almost 1, suggesting that emission line fluxes may indeed remain unchanged. Higher signal-to-noise spectra, however, are needed to investigate this in more detail.

3. DISCUSSION

The variability characteristic time scale is of particular interest when studying the underlying phenomena. In practice, the time scale depends on the definition, wavelength region, etc. To avoid ambiguity, we adopt a working definition that the typical time scale for variability is the time required for the source flux to change by 50%. Recalling that we do not see variability on time intervals less than a day, a $\sim 25\%$ change over 20 days, and a factor ~ 2 over 2.5 months it is probably reasonable to assume that the characteristic time scale is of order 1 month, give or take a factor ~ 2 .

The 1-month characteristic time scale for variability (neglecting any time dilation corrections for relativistic bulk motion) and the finite light travel time of the escaping radiation impose an upper limit on the size of the emitting region, $l \leq c\tau = 7.8 \times 10^{16}$ cm. Compared with the independently

estimated gravitational radius of $R_g = GM_{\text{BH}}/c^2 = 3.7 \times 10^{14}$ cm for the M87 nuclear black hole we obtain $l \lesssim 200R_g$. Thus the processes responsible for the observed variability must occur in the immediate vicinity of the central black hole.

The total energy output in the variable component is another important characteristic of the source. Our time sampling is too sparse to allow an accurate estimate of the quiescent state, but the observed changes of ~ 2 indicate that at least half of the nuclear flux is variable. Integrating the observed spectrum at its highest state between 100μ and 10 Kev, gives a nuclear continuum luminosity of order $\sim 3.0 \times 10^{42}$ ergs s^{-1} . This is only a small fraction of the mechanical luminosity derived for the jet (Bicknell & Begelman 1996) which is $\sim 10^{44}$ ergs s^{-1} . Even so, the total power released by the BH in M87 is only a very small fraction of the Eddington limit, $L_{\text{tot}} \sim 10^{-4}L_{\text{Edd}}$, indicating that the central engine operates in a highly sub-Eddington regime. The low optical luminosity and the sub-Eddington accretion supports the advection dominated accretion flow (ADAF) model advocated for this object by Reynolds et al. (1996).

Three possible explanations for the observed variability are i) tidal disruption of a star falling into the black hole (Hills 1975), ii) instabilities in the relativistic accretion disk (Sunyaev 1973; Shakura & Sunyaev 1973), and iii) jet related processes (Kollgaard 1994, Camenzind & Krockenberger 1992).

Although dwarf stars will cross the event horizon before being tidally disrupted, giant stars with densities $\sim 7 \times 10^{-5}$ g cm^{-3} can be disrupted at a distance of $\sim 7R_g$ from the M87 black hole. The time scale for sudden disruption is a few days, and the orbital period of the disrupted material is about two months in either a Schwarzschild or Kerr metric. The expected frequency of tidal disruptions is $\sim 10^{-3}$ yr^{-1} . Given this low frequency, continuing variability will argue against tidal disruption of stars.

If the variability is caused by instabilities in a “classical” accretion disk (e.g., hot spots), the variations in the observed flux are caused by relativistic boosting by the radial component of the orbital motion. In this case the characteristic time scale is approximately given by the orbital period, and the variability will be quasi-periodic depending on the spot life time. The shortest rotational period around a $2.5 \times 10^9 M_\odot$ black hole is ~ 17.3 days in the Schwarzschild metric and ~ 2.3 days in the Kerr metric. Hence, a detection of quasi-periodic variability on time scales shorter than ~ 17 days would argue against a nonrotating black hole, and time scales shorter than ~ 2 days would basically exclude the accretion disk as the source of the observed variability. Whatever the geometry, however, a very bright spot relative to the rest of the disk is needed to reproduce the observed amplitude.

In ADAF models the advective flow will suppress variability due to relativistic effects close to the event horizon. However, variations in the accretion rate may power variations in the relativistically boosted jet.

Superluminal motion is often observed at the base of relativistic radio jets. M87 is no exception (Biretta, Zhou & Owen 1995). The sudden brightening and apparent motion is attributed to

injection of relativistic plasma into the jet. If the injected material carries angular momentum from the accretion disk, it may follow a helical trajectory and produce a quasi-periodic “lighthouse effect” because of Doppler beaming and boosting (Camenzind & Krockenberger 1992). This model successfully explains the large simultaneous flux variations observed in some blazars over many decades in frequency from GHz to X-rays (Schramm et al. 1993, Wagner et al. 1995).

In order for the lighthouse effect to work in M87, at least some plasma in the jet must be moving very close to the line of sight. Given that the inclination of the M87 jet is $\sim 30^\circ$, and that the opening angle of the inner jet is $\sim 6^\circ$ (Biretta 1994) such a relativistic boosting can only occur if it is generated very close to the base of the jet in the region where the jet is becoming collimated.

We note that from the ground the usual seeing conditions make it very difficult to measure reliably the variability of the relatively faint nucleus against the stellar background. The current observations can not distinguish between variability originating in the accretion disk and/or variability in the base of the jet enclosed by the FOS aperture ($r \leq 0.13''$; $r \leq 9$ pc). However, further monitoring with appropriate sampling and polarization measurements may identify the source of variability. Nonetheless, these observations have established that M87 displays yet another BL Lac-like property.

In summary, M87 has now been shown to possess the following properties in common with the BL Lacs:

- it is an elliptical galaxy
- it is a FR I radio source
- it is a LINER
- it has a relativistically boosted jet
- it displays superluminal motions in the jet
- it has a strongly variable nucleus, both at optical and X-ray frequencies
- it has an underlying featureless power law continuum spectrum
- its spectral index is typical of BL Lacs

Unlike typical BL Lacs, M87 has a faint nucleus relative to the host galaxy and would not be detected as a BL Lac if it were much further away. Our results are consistent with the idea that the faintness of the nucleus is primarily due to the relatively large angle between the jet axis and the line of sight.

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FIGURE CAPTIONS

Fig. 1.— Brightness profiles of the nuclear region of M87 obtained from the binary search target acquisition data. Shown are four epochs of observation encompassing the observed range of variations. The other two epochs (not shown for clarity) show comparable variation. Each line represents a one dimensional image profile of the $1''.29 \times 3''.7$ aperture projected onto the galactic center. The images are shifted, so that the centers of the nuclear profiles are aligned. The two vertical dashed lines indicate the $1''.01$ region used for estimating the nuclear flux. The insert represents the radial profile of the peakup series for the 4 May 1995 observation. The dashed line is a scaled profile of a star obtained in a peakup series through the same $0''.26$ circular aperture.

Fig. 2.— Time variation of the nuclear flux measured from the binary search data (filled circles) and from the peakup series (open circles). The 1σ error bars are about 5% and 2.5% for the BS and PU data, respectively. The error bars for the galactic component (stars) are smaller than the symbols and are not plotted. The constant flux ratio between the $0''.26$ and $1''.01 \times 1''.29$ apertures is close to what is expected for the relative transmission of a point source (Keyes et al. 1995).

Fig. 3.— The two spectra of M87’s nucleus obtained through the $0''.26$ circular aperture. Each spectrum has been smoothed with a 3-pixel boxcar to better represent the true resolution. The ratio of the two spectra is shown in light gray in the lower panel. The continuous dark line is a simple linear regression fitted to the ratio. Note the dips at the positions of the emission lines.

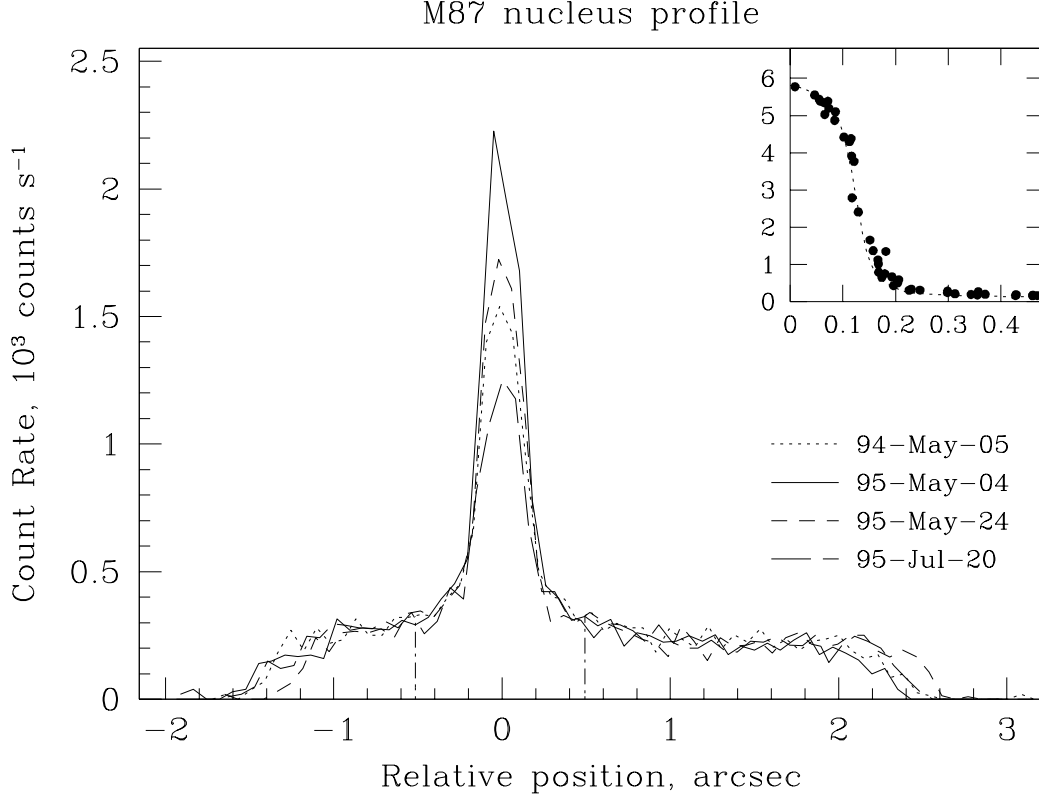


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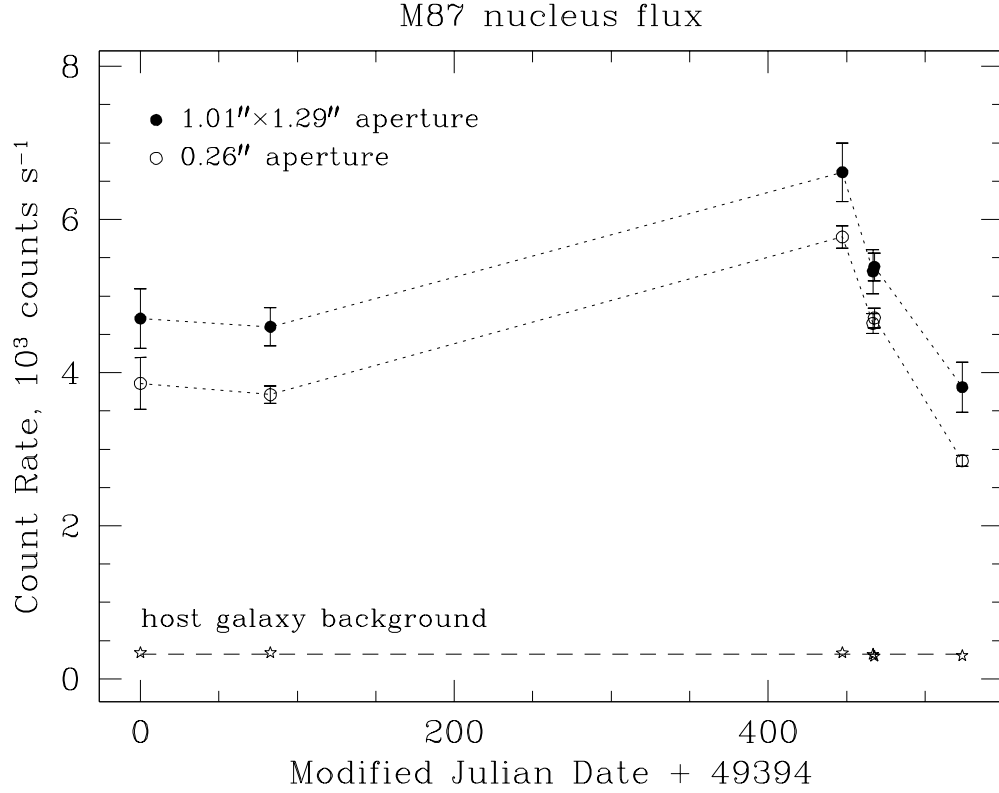


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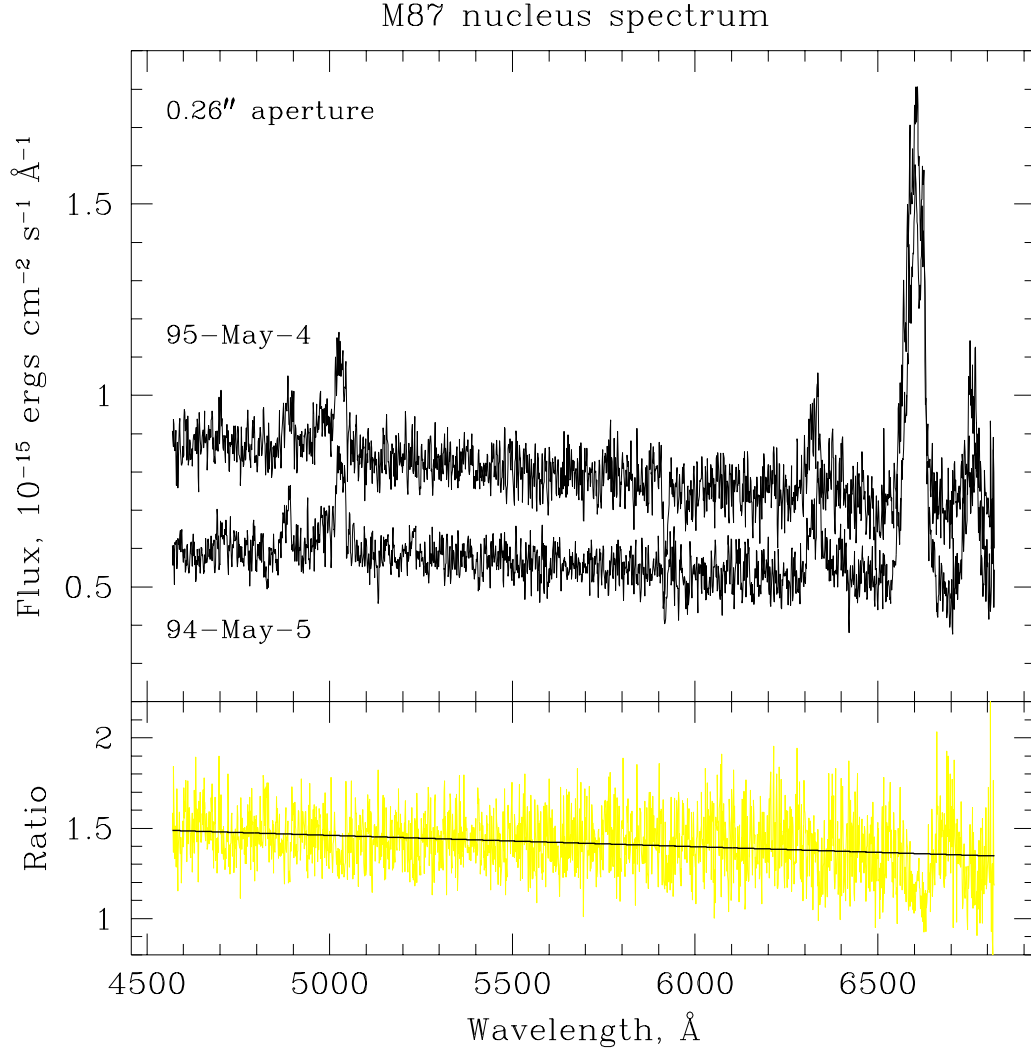


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